

International Conference on Industrial Engineering

## Modeling Cutting Force in Micro-Milling of Ti-6Al-4V Titanium Alloy

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### Abstract

This work presents a finite element method (FEM) based micro-end milling cutting force modeling of Ti-6Al-4V titanium alloy microchannels. Ti-6Al-4V is one of the widely acceptable titanium based alloys for medical as well as aerospace applications due to its advantageous properties like; corrosion resistance, larger strength to weight ratio, non-toxic nature and bio-compatibility. Johnson-Cook constitutive equation is used for the FEM model with due consideration of effects of strain, strain rate and temperature on the material property and failure parameters considered as the chip separation criterion. Simulation of stress distribution, temperature distribution and cutting forces prediction during micro-end milling of Ti-6Al-4V alloy is performed by ABAQUS/Explicit 6.12 software with incorporation of tool edge radius effect, which is more common in downscaling of the process. Predicted cutting forces model results are validated by conducting micro-end milling experiments. The trend of the predicted cutting forces results shows in good agreement with experimental results.

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Peer-review under responsibility of the organizing committee of the International Conference on Industrial Engineering (ICIE-2015)

**Keywords:** Micro-end milling, titanium alloy, microchannel, finite element method, von-Mises stress, size effect

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### 1. Introduction

The need for production of micro components is increasing with increasing demand for enhancement of product performance and reduction of weight and cost in many industries such as medical instrumentation, aerospace, automobile, electronics, etc [1]. In general, micro components can be produced by various methods such as

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lithography, laser machining, ion beam machining, electro-discharge machining, electro-chemical machining and mechanical micromachining [1,2]. Among these mechanical micromachining methods such as; micro-end milling shows a great promise in the manufacturing of these micro components with 3D features, higher aspect ratio, tolerable surface quality and applicability to wide range of engineering materials such as metals, metal alloys, non-metals, composites, ceramics, etc [3,4]. Titanium alloy Ti-6Al-4V is one of such ideal materials that provides the excellent properties like; high specific strength, corrosion resistance, fracture resistance, non-toxicity and biocompatibility; which makes it suitable for micro-feature based applications in aerospace, chemical, medical and many more [5,6]. However, Ti-6Al-4V alloy also possesses difficulty in machining due to its high temperature strength, relatively low modulus of elasticity, low thermal conductivity and high chemical reactivity which promotes reactivity of titanium with tool and leads to accelerated tool wear and uneven micro-burr formation [7,8].

Moreover, downscaling of conventional milling to micro-milling brings several problems related to size effects, micro-burr formation, tool wear and sudden tool breakage, etc [6,8]. Since micro-milling tool stiffness is low due to high aspect ratio (length/diameter), increase of forces in the micro cutting process will cause tool deflection or cause imperfection on the final product and even cause tool breakage if not minimized [9]. Therefore, an accurate prediction of cutting forces in micro-milling is essential. In micro-milling, uncut chip thickness is comparable to the tool edge radius known as size effect. This size effect associated with ploughing and elastic recovery causes nonlinear increase of specific cutting forces at low feed rates [10,11].

Therefore, micro-milling of Ti-6Al-4V alloy is a two-fold challenge: one due to unfavourable material properties for machining and another due to downscaling of the process. FEM based techniques are good compliments with the advancement of recent computational speed to experimental intensive, mechanistic approaches and offer a reasonable insight to the machining process for selection of cutting parameters to avoid premature wear and breakage of the tool [10-12]. There are several examples of 2D and 3D finite element method simulation of macro-milling process of Ti-6Al-4V alloy to study cutting forces, chip formation, cutting temperature and cutting tool wear under different process parameters [13-15]. However, there are limited applications of finite element based modeling and simulation of micro-milling of Ti-6Al-4V alloy, so far. Özel et al. [6] utilized FE simulation to predict temperature and wear development in micro-milling of Ti-6Al-4V alloy.

In the present study, a FEM model is proposed for prediction of cutting forces, stress generation and temperature distribution in micro-end milling of Ti-6Al-4V. Micro-end milling experiments have been performed for manufacturing of microchannels on Ti-6Al-4V workpiece using 400  $\mu\text{m}$  diameter two fluted uncoated tungsten carbide micro flat-end mills. Experimental results are verified with proposed model predicted results in order to assess the validity of the FEM model.

## 2. Micro-end milling cutting force modeling an FEM approach

A plane strain based orthogonal cutting force model with tool edge radius effect has been performed for micro-end milling process as shown in Fig. 1 using ABAQUS/Explicit 6.12 software. Fig. 2 shows the schematic representation of cutting process by a micro-end mill cutter.

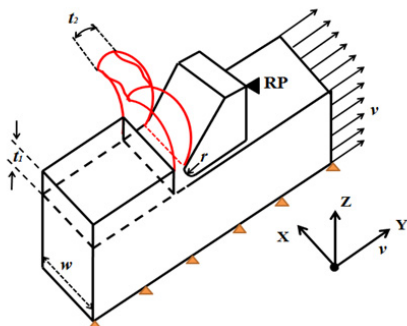


Fig. 1 FEM model of orthogonal cutting

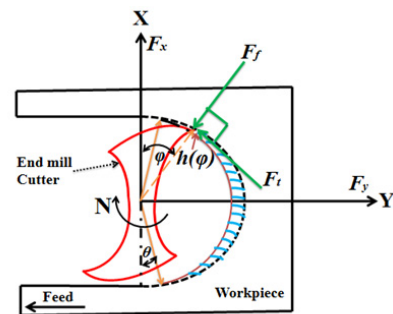


Fig. 2 Micro-end milling with two fluted cutter

The cutting tool used for the modeling purpose is consider as an isothermal rigid body and represented by the reference point (RP) to acquire the data value [12]. The size of the generated mesh is comparable with tool edge radius in order to maintain the simulation precision. The tool is restricted in all directions and workpiece travels towards the tool with uniform velocity  $v$  in Y-direction. The uncut chip thickness ( $h$ ) in micro-end milling process varies with cutter rotation angle and calculated by Eq. 1.

$$h(\varphi) = f_t \sin(\varphi), \quad (1)$$

where,  $\varphi$  is related to positioning angle of the tool and  $f_t$  is feed per tooth. Cutter rotation, feed direction and cutting force directions were also shown in Fig. 2.

### 3. Material properties and damage criterion for chip formation

Generally two types of approach are used to simulate the chip formation in Ti-6Al-4V titanium alloy: (a) material damage criterion or (b) modified material model with temperature dependent material softening approach [16]. However, literature also suggests about higher temperature generation during machining of titanium alloy due to low thermal conductivity of the material and effect of flow softening and strain hardening effect reduces as temperature increases [17]. As high strain and high temperature occur during machining of titanium alloy [15], flow stress will not be affected much by the flow softening phenomenon. Therefore, the more popular traditional Johnson-Cook material constitutive model [18] with material damage criterion [19] has been used for the proposed model. The Johnson-Cook model is described by the expression of average flow stress given by Eq. 2.

$$\bar{\sigma}_{JC} = \left[ A + B(\varepsilon)^n \right] \times \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \times \left[ 1 - \left( \frac{T - T_0}{T_m - T_0} \right) \right], \quad (2)$$

where  $\varepsilon$  is the equivalent plastic strain,  $\dot{\varepsilon}$  and  $\dot{\varepsilon}_0$  are the equivalent and reference plastic strain rates,  $T$ ,  $T_m$  and  $T_0$  are the material's cutting zone, melting and room temperature, respectively,  $n$  is the strain hardening index, and  $m$  is the thermal softening index. Johnson-Cook Parameters  $A$ ,  $B$  and  $C$  represent the yield strength, strain and strain rate sensitivities of the material. The material properties Table 1 from Wu and Zang test results were used for the FEM modeling [15].

Table 1. Mechanical properties and Johnson-Cook parameter of Ti-6Al-4V alloy [15].

Details		Parameters			
Mechanical properties	Density [Kg/m <sup>3</sup> ]	Elastic modulus [MPa]	Poisson's ratio	$T_m$ [°C]	$T_0$ [°C]
Value	4430	123	0.34	1570	20
Johnson Cook model	$A$ [MPa]	$B$ [MPa]	$n$	$C$	$m$
Value	1000	780	0.47	0.033	1.02

Johnson-Cook failure model [19] was used as a damage initiation criterion. This model takes into account the influence of stain, strain rate, and temperature on material failure shown in Eq.3. The five failure parameters of the Johnson-Cook model are shown in Table 2 [15].

$$\varepsilon_{f \text{ ailure}} = \left[ d_1 + d_2 \exp \left( d_3 \frac{P}{\bar{\sigma}_{JC}} \right) \right] \times \left[ 1 + d_4 \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \times \left[ 1 + d_5 \left( \frac{T - T_0}{T_m - T_0} \right) \right]. \quad (3)$$

Table 2. Johnson-Cook failure parameter of Ti-6Al-4V alloy [15]

Details	Parameters				
Fracture parameters	$d_1$	$d_2$	$d_3$	$d_4$	$d_5$
Value	-0.09	0.25	-0.5	0.014	3.87

The main cause of the heat generation and its thermal aspect in contact problem is friction. The coefficient of friction  $\mu$  has been taken as 0.5 for contact problem simulation purpose [15].

#### 4. Micro-end milling simulation of Ti-6Al-4V titanium alloy

FEM simulations of the micro-end milling process for Ti-6Al-4V alloy were performed under different cutting conditions (spindle speed of 15000 rpm to 35000 rpm; feed rate of 1-5  $\mu\text{m}/\text{tooth}$ ; and constant axial depth of cut of 30  $\mu\text{m}$ ). Tool edge radius of 2  $\mu\text{m}$  is used for the modeling purpose. Workpiece material is assumed to be viscoplastic material, as this assumption is more practical and reduces the computational time significantly with very small deviation in the results of cutting forces, tool wear and temperature [20]. von-Mises stress calculates the yield criterion and fracture strength of the material and once its value exceeds the average flow stress value, yielding takes place. However, experimental measurement of these simulation variables like; stress, strain, temperature are very difficult and numerical simulation or analytical simulation is more preferred as alternatives of direct measurement. Therefore, von-Mises stress distribution and temperature distribution is simulated for the micro-end milling of titanium alloy Ti-6Al-4V. One of simulation results at uncut chip thickness 1  $\mu\text{m}$  and cutting depth of 30  $\mu\text{m}$  at cutting speed of 31.415 m/min (corresponding to 25000 rpm spindle speed) is shown in Fig. 3. The stress distribution also shows that lower value of von-Mises stress occurs on the machined surface and it is increasing towards the cutting edge of the tool. This is due to the higher force required at the cutting edge of the tool in the shear zone for chip formation [21]. The maximum stress occurred in the primary shear band and the value was 2467 MPa. However, the increase of stress value may be due to the size effect of the micro-milling process. The maximum value of temperature is 845.3  $^{\circ}\text{C}$  which is quite high. This value is in the range of the temperature of macro-milling of Ti-6Al-4V alloy [15] and results of this higher temperature leads to accelerated tool wear in micro-milling process [6].

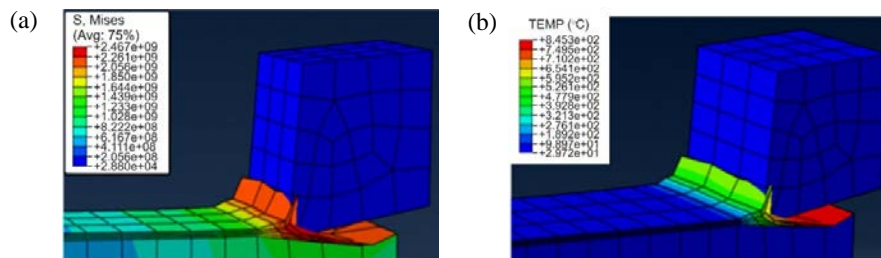


Fig. 3. Predicted (a) von-Mises stress distribution and (b) Temperature distribution at cutting speed of 31.415 m/min feed rate of 1  $\mu\text{m}/\text{tooth}$  with depth of cut of 30  $\mu\text{m}$

#### 5. Model validation through experimental results

The experimental setup for validation of FEM model results is shown in Fig. 4 (a). SEM image of the used tool and microscopic image of fabricated microchannels at spindle speed of 25000 rpm, feed rate of 1  $\mu\text{m}/\text{tooth}$  with depth of cut of 30  $\mu\text{m}$  are shown in Fig. 4 (b) and (c) respectively.

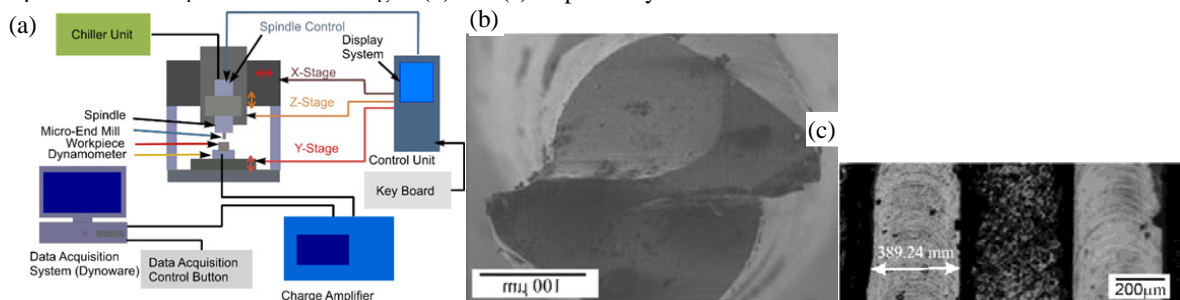


Fig. 4. (a) Experimental setup; (b) SEM image of micro-end mill after manufacturing of microchannels;

(c) Microscopic images of microchannels at spindle speed of 25000 rpm, feed rate of 1  $\mu\text{m}/\text{tooth}$  with depth of cut of 30  $\mu\text{m}$

Experiments are performed on a multi-purpose micro machining center (Model No. DT-110, Mikrottools Ltd.) having a maximum spindle speed of 60000 rpm and run out of less than 1  $\mu\text{m}$ . Two-flute tungsten carbide micro-end mill with 400  $\mu\text{m}$  tool diameters and 2  $\mu\text{m}$  of tool edge radius is used to produce microchannels on Ti-6Al-4V workpiece having dimension of 75 mm x 45 mm x 3 mm. Table 3 shows the values of different cutting parameters (cutting speed, feed and axial depth of cut) used for microchannel fabrication. Cutting forces are acquired by piezo electric type force dynamometer (Kistler Type 9256C2) with sampling rate of 6000 Hz. The dynamometer having high natural frequency of over 5 kHz in all the three force directions makes it more reliable for measuring low cutting forces. However, tool wear and micro burr formation are not analyzed in the present work.

Table 3. Cutting condition used for fabrication of microchannels on titanium alloy Ti-6Al-4V

Details	Cutting parameters for dry cutting		
	Spindle speed [rpm]	Feed value [ $\mu\text{m}/\text{tooth}$ ]	Axial depth of cut [ $\mu\text{m}$ ]
Value	15000, 25000, 35000	0.5, 1.0, 1.5	30

## 6. Experimental validations of predicted results

To analyze the utility of proposed model, experimental cutting forces are used for validation. The experimental and FEM simulated cutting forces at spindle speed of 25000 rpm, feed rate of 0.5, 1.0 and 1.5  $\mu\text{m}/\text{tooth}$  and depth of cut of 30  $\mu\text{m}$  are compared in Fig. 5 (a), (b), (c) and 6 (a), (b), (c).

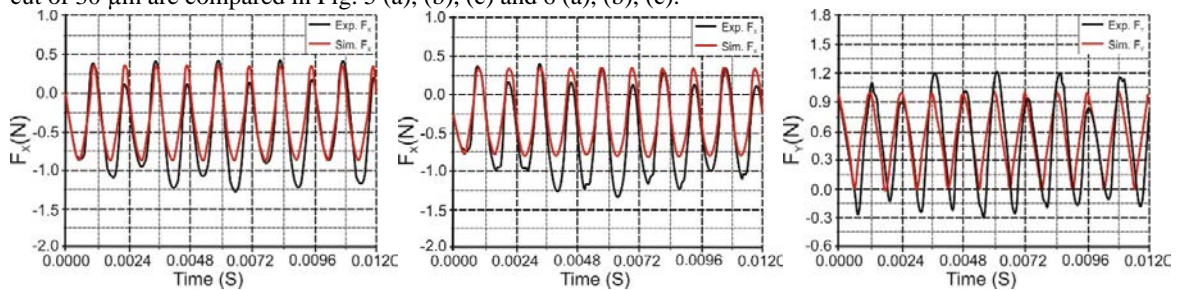


Fig. 5. Comparison of cutting force  $F_x$  (a) 0.5  $\mu\text{m}/\text{tooth}$  (b) 1.0  $\mu\text{m}/\text{tooth}$  (c) 1.5  $\mu\text{m}/\text{tooth}$

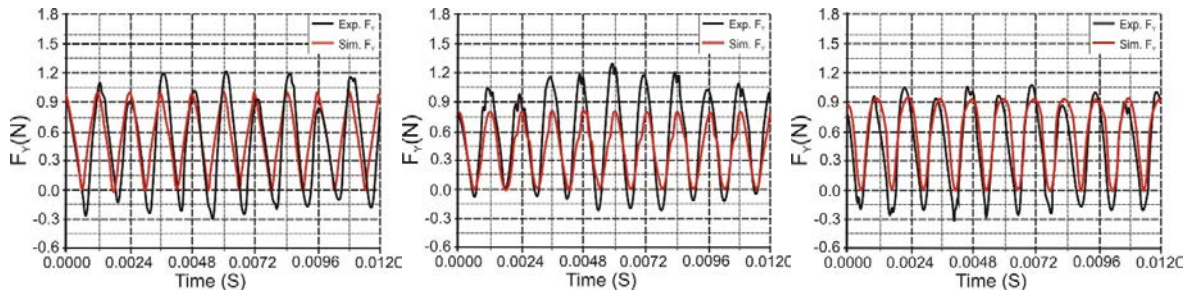


Fig. 6. Comparison of cutting force  $F_y$  (a) 0.5  $\mu\text{m}/\text{tooth}$  (b) 1.0  $\mu\text{m}/\text{tooth}$  (c) 1.5  $\mu\text{m}/\text{tooth}$

The simulated cutting forces  $F_x$  and  $F_y$  show good agreement with experimental results. However, small discrepancy of simulated and experimental forces is observed as tool dynamics, tool wear affects during the milling process are not considered in the model, which always predicts same force in each pass of the cutting edge. However, in actual experimental scenario tool dynamics and tool wear of the material will cause variations of cutting forces in different passes of the cutting edge. From Fig.5 and Fig. 6 it can also be observed that experimental cutting forces increase with increase in number of cutter rotation. This may be because of the accelerated tool wear and edge rounding due to high cutting temperature created in the micro-end milling of Ti-6Al-4V alloy.



## 7. Conclusions

The present paper described the cutting force modeling in micro-end milling of titanium alloy Ti-6Al-4V using ABAQUS/Explicit finite element method. The proposed FEM model simulated stress distribution, temperature distribution and cutting force generation considering the effects of tool edge radius, uncut chip thickness, cutting speed and feed rate. Maximum Von-Mises stress and cutting temperature were found to be more than those of macro-milling of Ti-6Al-4V alloy. These can be related to the effect of tool edge radius and low feed values applied in micro-end milling. The finite element simulation of specific cutting forces showed the size effects in micro-end milling process. The simulated cutting forces were successfully validated with experimental results.

## 8. Acknowledgement

This article is a part of the bilateral research project «Modeling and analysis of high speed hybrid micromachining»:

1. The reported study was partially supported by DST, Govt. of India, research project No. INT/RUS/RFBR/P-226.
2. The reported study was partially supported by RFBR, research project No. 15-58-45017 ИИД\_а.

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